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Research Article

Numerical Analysis of Cold Injury of Skin in Cryogen Spray Cooling for Laser Dermatologic Surgery

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Abstract

In laser dermatologic surgery, cryogen spray cooling (CSC) is used to avoid unwanted thermal damage such as scars from skin burning due to the melanin absorption of the laser beam. As the cryogen is fully atomized from the nozzle, temperature of the droplets can quickly drop below -60 °C because of evaporation. Such low temperature may lead to cold injury of skin. Therefore, spray cooling process should be accurately controlled during clinical practice to achieve sufficient protection and avoid cold injury. This study presents a numerical analysis for cold injury of skin in cryogen spray cooling for dermatologic laser surgery by a newly developed hest transfer model. For the freezing of skin cells, heat conduction equation was used to describe frozen and unfrozen zones, and heat capacity method was utilized for mushy zone to consider the phase change of tissue. A realistic boundary condition was implemented to simulate the cooling effect during cryogen spray cooling by a generalized correlation for the dynamic heat transfer coefficient. By tracking the front of the tissue phase change, the model can be used to predict the movement of the harmful isothermals. With this model, the severity of cold injury is quantified under various clinical conditions and the effects of initial temperature as well as the spurt duration on possible cold injury of skin are investigated. The results show that 100~150ms spray cooling duration is appropriate to avoid non-uniform cooling along the radial direction and also prevent potential cold injury. Lower room temperature (10~20°C) is recommended to achieve a deep penetration protection. Further development of new candidate cryogens with lower boiling point (e.g. R407C or R404a) are highly recommended to achieved a better cooling effect.

Keywords: Cryogen spray cooling; Port wine stain; Laser surgery; Cold injury; Numerical analysis

1. Introduction

Port Wine Stain (PWS) birthmark is a congenital and progressive vascular malformation of the capillaries in dermis, which occurs in approximately 0.3% of newborns (Alper et al., 1983). Laser treatment of PWS has been widely used in clinic, which is based on the principle of selective

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photothermolysis (Anderson et al., 1981). During the treatment, light (laser) is preferably absorbed by hemoglobin in PWS blood vessels, which will cause irreversible thermal damage, thrombosis, and, eventually, permanent photocoagulation in the PWS vessels. Unfortunately, a significant amount of energy in laser beam is absorbed by melanin in the basal layer of the epidermis, leading to skin dyspigmentation or hypertrophic scarring (Aguilar et al., 2001a and 2001b).

In order to protect the epidermis from non-specific heating, Cryogen spray cooling (CSC) was proposed (Pikkula et al., 2001; Nelson et al., 1995, 1996 and 2000; Edris et al., 2003). Prior to laser irradiation, the skin is pre-cooled by continuous impact of atomized cryogen droplets at fairly low temperature (below -60 ^{o}C) due to evaporation during cryogen spray.

To date, some experiment studies have been conducted to quantify the cooling effect of epidermis during CSC (Aguilar et al., 2001a, 2001b and 2002; Verkruysse et al., 2000). Experiment measurements found that the convective heat transfer coefficient of spray cooling, h, shows a strong dynamic variation during and after the spray (Aguilar et al., 2003a), and that the dynamics of h strongly depend on the spray distance. Furthermore, a large fluctuation of h over the margin of the spray was also observed in the experiments (Franco et al., 2005).

Most of existing studies on CSC focused on the cooling effectiveness and/or quantification of cooling effect. During CSC, as the cryogen is fully atomized from the nozzle, evaporation of the droplets may quickly drop the cryogen temperature below -60 ^{o}C within a short spray distance. On the one hand, the cooling effect may be difficult to conduct deep enough to achieve basal layer of the epidermis due to the low heat conduction ability of human tissue. On the other hand, such a low temperature may lead to cold injury of skin. Therefore, the spray cooling process should be accurately controlled to be long enough to provide thorough protection of epidermis but short enough to avoid unwanted cold injury during clinical practice. All potential influence factors should be fully investigated, including initial temperature, maximal heat flux and spray duration.

Numerical analysis is effective to quantify the cooling capacity of CSC. However, most existing studies use a constant surface heat transfer coefficient during the simulation, which is inconsistent with experimental observation. Recently, we presented a simplified correlation of convection heat transfer coefficient in cryogenic spray cooling, based on recent experimental data (Li et al., 2007). The normalized convection heat transfer coefficient is represented as a function of both non-dimensional time and space, which can be used for a wide range of CSC conditions. The correlation has been employed in a newly developed two-dimensional CSC model to investigate the temporal and spatial variation of skin temperature during laser surgery (Aguilar et al., 2003a and Franco et al., 2005). However, the model needs to be further improved to take the cold injury during cooling process into consideration.

The motivation of this work is to develop a new theoretical model including the freezing of skin cells based on the early developed model of cryogen spray cooling of skin. With this model, possible cold injury of skin in cryogen spray cooling for dermatologic laser surgery was numerically analyzed. Variations of skin temperature under various spray conditions are examined to quantify possible cold injury of skin during CSC.

2. Theoretical model of CSC

For cooling the skin in laser surgery, the cryogen utilized is 1,1,1,2 tetrafluoroethane (also known as R134a) with boiling point T_b = -26.2 °C at 1 atm. Cryogen is usually kept in a container at saturation pressure, which is approximately 660kPa at 25 °C (95.7 psi). Through a straight-tube nozzle, cryogen will be atomized to small droplets. As the cryogen droplets reach the tissue surface, tissue will experience a quick cooling process to reach a low temperature (Aguilar et al., 2001a).

Figure 1 shows the skin model, which is an axisymmetric two-dimensional domain. As shown in the figure, the skin model consists of two layers: an epidermal layer and a dermal layer. The thicknesses of the epidermal and dermal layer are 75μm and 925μm, respectively (Aguilar et al., 2003a; Sun et al., 2006).

During the freezing of the biological tissue, the conversion of water to ice does not complete at a single temperature, but rather takes place progressively over a temperature range, e.g. -0.5~-10 °C. The tissue between this temperature range can be referred to as mushy zone, which is a buffer region between the frozen and unfrozen states.

Since the spray duration is usually completed within a short period (e.g. tens of millisecond) the effect of the blood perfusion can be neglected. Therefore, the bio-heat equation is reduced to classic heat conduction equation, which can be written as follows in frozen and unfrozen zone, respectively:

$$\rho_u c_{pu} \frac{\partial T}{\partial t} = k_u \nabla^2 T, \quad \text{For unfrozen zone} \tag{1}$$

$$\rho_f c_{pf} \frac{\partial T}{\partial t} = k_f \nabla^2 T, \quad \text{For frozen zone} \tag{2}$$

where ρ is the density, c_p is the specific heat, k is the thermal conductivity, T is the temperature, and t is the time. Subscripts f and u represent frozen and unfrozen region, respectively. As for mushy zone, heat conduction equation is written as follows by heat capacity method:

$$\rho_m c_{pm} \frac{\partial T}{\partial t} = k_m \nabla^2 T + Q \tag{3}$$

$$\rho_m c_m = f_f \cdot \rho_f c_f + f_u \cdot \rho_u c_u \tag{4}$$

$$k_m = k_f f_f + k_u f_u \tag{5}$$

$$\begin{aligned} Q &= -L\frac{\partial \dot{m}_u}{\partial t} = -L\frac{\partial \rho f_u}{\partial t} \\ &= -\rho L \frac{\partial f_u}{\partial t} = -\rho L \frac{\partial f_u}{\partial T}\frac{\partial T}{\partial t} \end{aligned} \tag{6}$$

$$f_f + f_u = 1 \tag{7}$$

where Q is the heat released due to solidification, f_u is the unfrozen fraction in the mushy zone, f_f is the frozen fraction in the mushy zone, and L is latent heat of solidification. Subscript m represents mushy zone. Substituting equation (6) in equation (3), we can obtain:

$$(\rho_m c_{pm} + \rho L \frac{\partial f_u}{\partial T}) \frac{\partial T}{\partial t} = k_m \nabla^2 T \tag{8}$$

Owing to a very thin mushy zone, the liquid fraction in the mushy zone can be assumed to be a linear function of temperature:

$$f_u = \frac{T - T_f}{T_u - T_f} \tag{9}$$

where T_u and T_f represent the upper and lower limit of the phase change and set to be -0.5 and -10 ^{o}C, respectively (Sun et al., 2006).

$$\frac{\partial f_u}{\partial T} = \frac{1}{T_u - T_f} \tag{10}$$

Substituting equation (10) in equation (8), and defining apparent heat capacity as:

$$\rho_a c_a = \rho_m c_{pm} + \frac{\rho L}{T_u - T_f} \tag{11}$$

$$\rho_a c_a \frac{\partial T}{\partial t} = k_m \nabla^2 T \tag{12}$$

On the skin surface (z=0), the standard convection condition was used to describe the cooling effect of CSC:

$$-k \left. \frac{\partial T}{\partial z} \right|_{z=0} = h_{\mathrm{csc}} [T(r, 0, t) - T_{\mathrm{film}}] \tag{13}$$

where T_{film} is temperature of cryogen film on the cooling surface. h_{csc} is heat convection coefficient during CSC.

In most existing models of CSC for laser dermatology, Newton's law of cooling was employed and the value of a heat convection coefficient h was usually assumed constant over the entire spray area and during the entire spray duration (Verkruysse et al, 2000). Recent experiments (Aguilar et al, 2003a and Franco et al, 2005) found that h_{csc} is a strong function of both time and space. Based on these experimental data, a generalized correlation between normalized convection heat transfer coefficient ($h^* = h_{csc} / h_{o,max}$) and the non-dimensional time ($\tau = t / t_{max}$) and non-dimensional space ($r^* = r / r_{spray}$) has been proposed as follows (Li et al, 2007):

$$\begin{cases} h^*(r^*,\tau)=\dfrac{h_{csc}}{h_{o,max}}=\begin{cases} h_o^*(\tau) & 0\le r^*\le 0.4 \\ [5(1-r^*)]/[3h_o^*(\tau)] & 0.4<r^*\le 1.0 \end{cases} & \tau\le 1.0 \\ h^*(r^*,\tau)=\dfrac{h_{csc}}{h_{o,max}}=\begin{cases} h_o^*(\tau) & 0\le r^*\le 0.2(\tau+1) \\ h_o^*(\tau)+\dfrac{(5r^*-\tau-1)}{(4-\tau)}\times[0.09(\tau-1)-h_o^*(\tau)] & \\ & 0.2(\tau+1)<r^*\le 1.0 \end{cases} & 1.0<\tau<4 \\ h^*(r^*,\tau)=\dfrac{h_{csc}}{h_{o,max}}=h_o^*(\tau) \qquad 0\le r^*\le 1.0 & \tau\ge 4.0 \end{cases} \tag{14}$$

where $h_{o,max}$ is the maximum value of heat transfer coefficient during spray, t is the spray duration and t_{max} is the time when $h_{o,max}$ occurs. r^* is the dimensionless radius, r is the radius, and r_{spray} is the maximum spray cooling area which is usually exposed to air. The normalized convection heat transfer coefficient at the center of spray, h_o^*, is a piece-wise function of τ:

$$h_o^*(\tau)=\begin{cases} \tau & \tau\le 1.0 \\ 1.0-0.35(\tau-1) & 1.0<\tau\le 3.0 \\ 0.3-0.02(\tau-3) & 3.0<\tau\le 8.0 \\ 0.2-0.0125(\tau-8) & 8.0<\tau \end{cases} \tag{15}$$

The experimentally measured values of $h_{o,max}$ and t_{max}, as well as the temperature of the liquid cryogen layer on the substrate, T_{film}, are given in Table 1.

Considering the depth of the skin is far less than the width, symmetric adiabatic boundary is set for the domain center. All other boundaries are set to be the tissue temperature of 37°C.

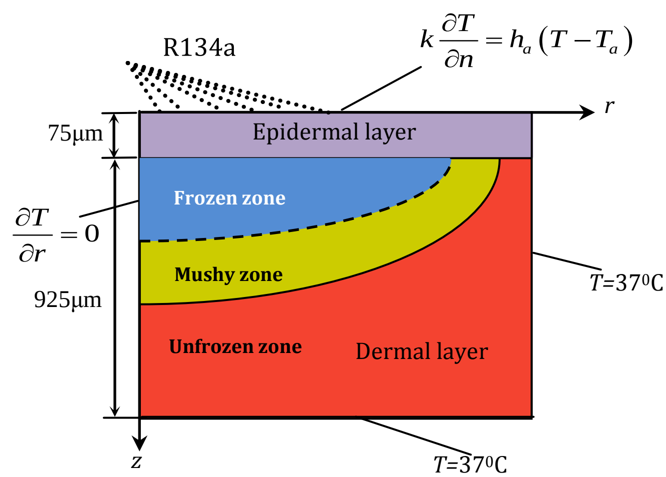


Fig 1. The computational domain and boundary conditions of the two-dimensional axisymmetric model for the cutaneous cryogen spray cooling

Table 1 Experimental data of $h_{o,max}$, t_{max}, T_{film} for different spray distance (Aguilar et al., 2003a)

Spray distance (mm)	$h_{o,max}$ (kW/m^{2}K)	t_{max} (ms)	T_{film} (^{o}C)
30	15.39	10.62	-48.5
40	11.37	12.31	-52.6
50	9.80	18.08	-54.4
60	8.82	18.27	-56.5

The governing equations (1), (2) and (8) together with the corresponding boundary conditions (13~15) and initial conditions are solved numerically by an in-house computer code based on the finite-volume method.

The normalized convective heat transfer coefficient, $h^*(r^*,\tau)$, has been introduced into our two-dimensional CSC model of skin over the spray area, together with the apparent heat capacity method for tissue solidification. The model is then used to simulate the cryogen spray cooling in dermatological laser surgery of PWS before laser is fired. In the clinical practice, the spurt duration ranges from 60 ms to 100 ms and the spray distance ranges from 30 mm to 60 mm. The size of various skin layers and the corresponding thermal physical properties used in the computation are given in Table 2. The initial temperature of skin is assumed to be 37 ^{o}C.

Table 2 Thermal physical properties used in the apparent heat capacity method (Aguilar et al., 2003a; Sun et al., 2006)

Properties	Epidermal Layer	Dermis Layer
D/μm	75	925
ρ /kg·m^{-3}	1000	1000
L (J/Kg)	0	217100
k, W(m·K)$^{-1}$	0.209 (unfrozen) 0.209 (frozen)	0.498 (unfrozen) $(273-T)^{1.156}\times 0.0039+1.553$ (frozen)
ρC, J/(kg·K)$^{-1}$	3530 (unfrozen) 3530 (frozen)	3150 (unfrozen) $521.4 + 4.65T$ (frozen)

3. Results and discussions

3.1 Dynamic and spatial behavior of skin temperature

Figure 2 shows dynamic variation of the temperatures at different depth: z = 0, 35, 75, 500 and 1000 μm at the spray center with spray distance of 50 mm. As can be seen from the figure, the surface temperature (z = 0) at the center of the spray firstly reduces to a minimum value at the early stage of the spray, and followed by a short period of almost constant values before it slowly increases. This interesting dynamic behavior is in consistency with the experimental observations by many researchers (Aguilar et al., 2003a, 2003b and Franco et al., 2005). We can also find that the cooling effect is strongly decayed along the axial direction. For example, in 250 ms, the temperature of the skin tissue at the center of the spray (z = 0) reduces to -10 °C while at the depth of 500 μm the tissue temperature has only 2°C reduction. Such a large difference in the temperature variation at different skin depth is attributed to the low thermal conductivity of skin tissue. At the interface between the epidermis and dermis (z = 75 μm), the final temperature is about 12 °C after 300 ms spray duration, which is not low enough to avoid the hyperthermal injury because the melanin concentration is high here.

All existing models for cryogen spray cooling of laser dermatological surgery assumed a spatially uniform value of h. Experimental measurements have shown a spatial variation in both the heat flux and temperature (Pikkula et al., 2004). We have introduced such a spatial variation in the present model, and Figure 3 reflects such variations of the surface temperatures at various radial locations: r = 0 ~ 5 cm. As one can see from Figure 3, the minimum temperature that can be reached varies significant along the radial direction, with a very low temperature reached at the center of the spray but a much higher temperatures for the location farther away from the center of the spray. Such a variation of the surface temperature is in consistent with the experimental observations by Franco *et al*. (Franco et al., 2005), demonstrating a significant non-uniform cooling over the spray zone. As we can see from the figure, the cooling effect covers the entire area after about 100ms and an almost homogenous cooling effect on skin surface is achieved, from which it can be concluded that the spray duration should be long enough (e.g. 100ms) to avoid inhomogeneity cooling on spray area with a 5mm radius.

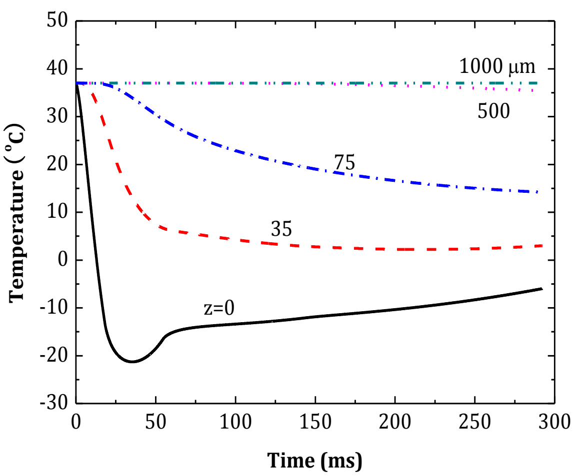


Fig 2. Dynamic variation of the tissue temperatures at various depth: z = 0, 35, 75, 500, and 1000 μm, respectively.

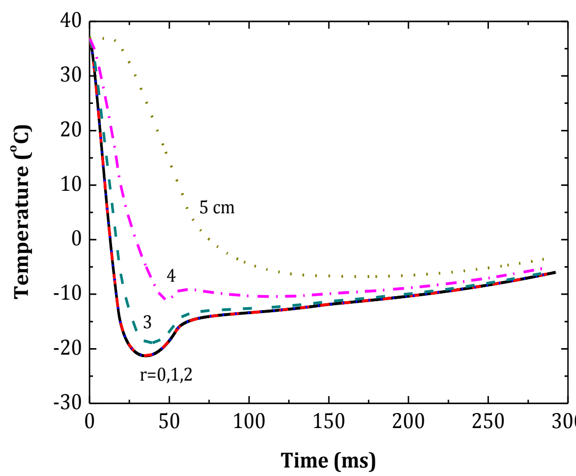


Fig 3. Spatial variation of the surface temperature.

Figure 4 shows the movement of the -0.5°C and -10°C isothermal (corresponding to the upper and lower limits of the phase change) at the center. At the beginning of spray, the cryogen droplets with very low temperature reach the skin surface and decrease the surface temperature quickly, so the movement of two isothermals is fast. The cooling effect transfers inward by heat conduction and the propagation of the cold slows down due to the low thermal conductivity of the human skin and continuous heating of the internal tissues, which leads to the reduction of the temperature gradient.

The frozen zone enlarged quickly and reaches the maximum at about 50ms. The mushy zone (area between two isothermals) enlarges at the beginning and reaches a maximum at about 210ms, followed by a continuous reduction. For the condition presented in Figure 4, the mushy zone couldn't get deep enough to reach deep epidermis and dermis interface to cover the entire epidermis.

These results indicate that usually (room temperature of 25°C and body initial temperature of 37°C), the cold injury is not a problem due to the low thermal conductivity of the skin. On the other hand, there might be some concern on the insufficient protection in the deep epidermis and the margin of the spray area. One needs to investigate all the possibilities to avoid such problems.

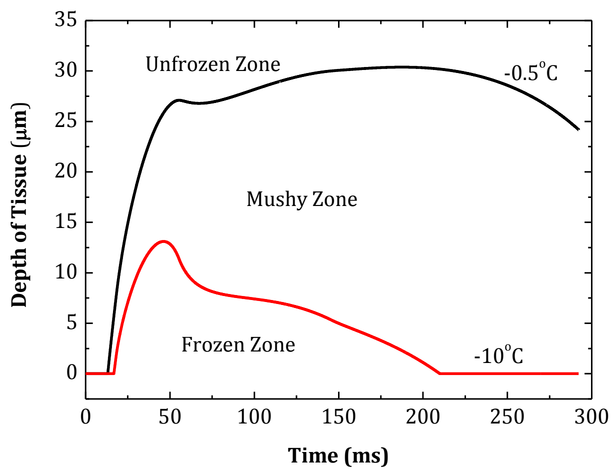


Fig 4. Movement of the -0.5°C and -10°C isothermals at the center of the spray area

3.2 Effect of initial skin temperature T_o

Skin is the biggest organ of the integumentary system. It covers the entire body and protects the body from outside. The skin is always vulnerable to the atmosphere, so the influence of the initial temperature of the skin is worth investigating.

The effect of T_o on the surface temperature dynamics is shown in Figure 5. It is found that the initial skin temperature has a strong effect on the minimum skin temperature that can be reached by CSC. Reducing the initial surface temperature from 37 to 10 °C, the minimum skin temperature due to CSC changes from -21 (Fig. 2) to -32 °C.

The effect of T_o on the movement of -0.5°C isothermal is given in Figure 6. It can be seen that the front of the mushy zone moves deeper into the skin as the initial temperature decreases. At T_o = 20 °C, the mushy zone will cover the entire epidermal layer at 250ms after the spray starts. The mushy zone can penetrate further deep into the dermis as T_o further reduced.

Figures 7 and 8 show the effect of T_o on the cooling rate of the spray center along the axial direction at two different time instants, 45 and 150 ms, respectively. Generally speaking, a higher initial temperature T_o leads to a higher cooling rate due to a larger temperature difference between the skin tissue and the cryogen spray. At 150 ms in Figure 8, the cooling rate shows a spike for the case with T_o =10 °C. Such a sudden increase in the cooling rate takes place at the location of the -0.5°C isothermal.

The potential of the skin cold injury at T_o = 10 and 20 °C is investigated in Figures 9 and 10 with 150 ms spurt duration. The cold injury determined not only by the temperature but also the cooling rate. The lethal cooling rate that leads to the formation of lethal intracellular ice formation (IIF) is about 19 °C/s (Sun et al., 2006) as shown in both figures, together with the epidermis/dermis and mushy zone/unfrozen zone interfaces.

As we can see from Figure 9, the mushy zone penetrates into the dermis, and the cooling rate gets its maximum at the same time but much higher than 19 °C/s, indicating possible cold injury of tissues deep in the dermis for the case with T_o = 10 °C. For the case with T_o = 20 °C shown in Figure 10, however, the cooling rate is high enough to cause cold injury at the upper dermis layer, but the mushy zone confined only in the epidermal layer. Similar results are found for the conditions with a higher T_o.

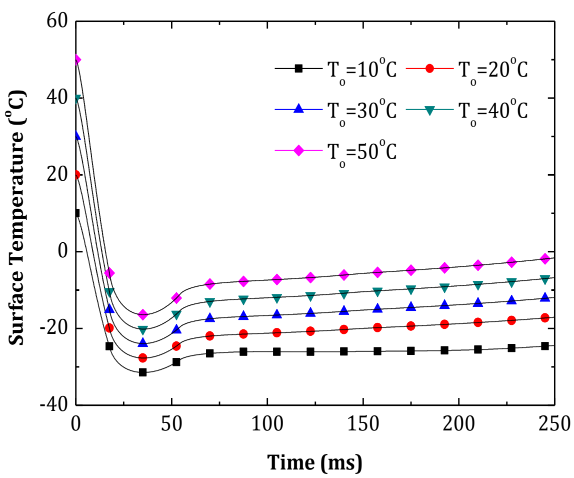


Fig 5. Effect of T_o on the surface temperature dynamics.

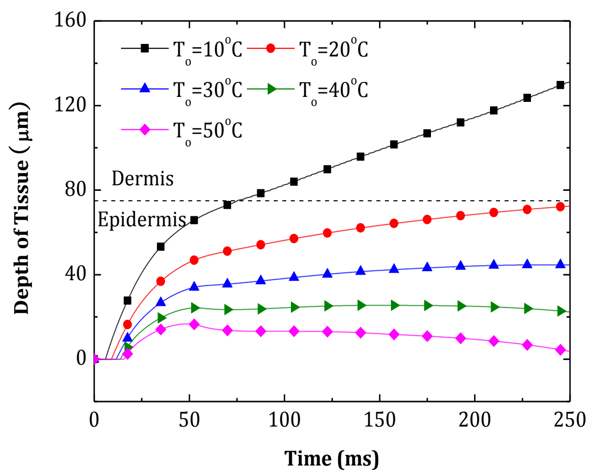


Fig 6. Effect of T_o on the movement of -0.5°C isothermal.

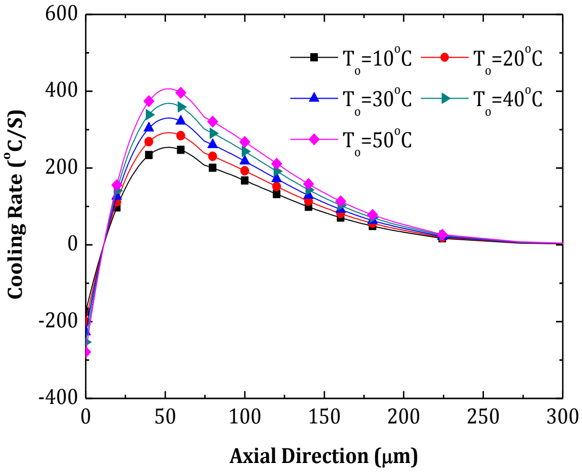


Fig 7. Effect of T_o on the cooling rate along the axial direction. (Center of the spray at 45ms)

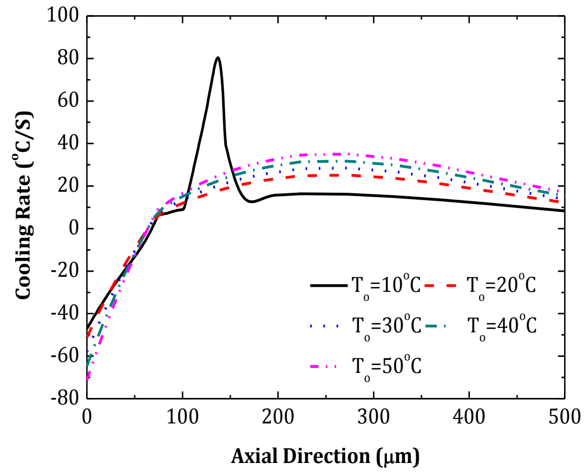


Fig 8. Effect of T_o on the cooling rate along the axial direction. (Center of the spray at 150ms)

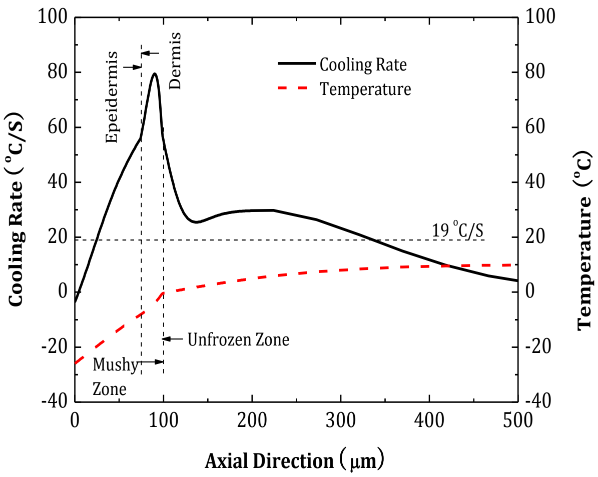


Fig 9. Distribution of the cooling rate and temperature of the spray center along the axial direction at T_o = 10 °C.

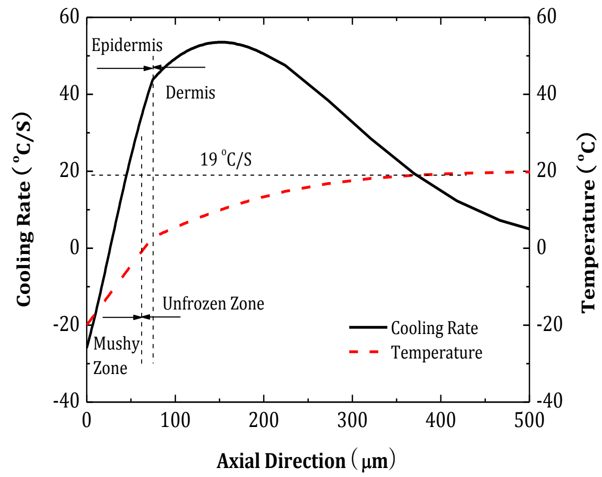


Fig 10. Distribution of the cooling rate and temperature of the spray center along the axial direction at T_o = 20 °C.

3.3 Effect of $h_{o,max}$ and t_{max}

The $h_{o,max}$ and t_{max} in the heat transfer coefficient correlation, Eqs. (14) and (15), are two important parameters that characterize the surface heat transfer during cryogen spray cooling. These parameters strongly depend on the kind of the cryogen, the nozzle placement and other spray conditions. A sensitivity study is performed here to examine the effect on the surface temperature dynamic, the inner temperature distribution and the movement of the harmful isothermals.

Figure 11 shows the effect of $h_{o,max}$ and t_{max} on the surface temperature variation in spray center area. As one can see from the figure, the minimum surface temperature decreases as $h_{o,max}$ increases. One can also find that the time at which the minimum temperature occurs is delayed and the minimum temperature duration is also lengthened as t_{max} increases.

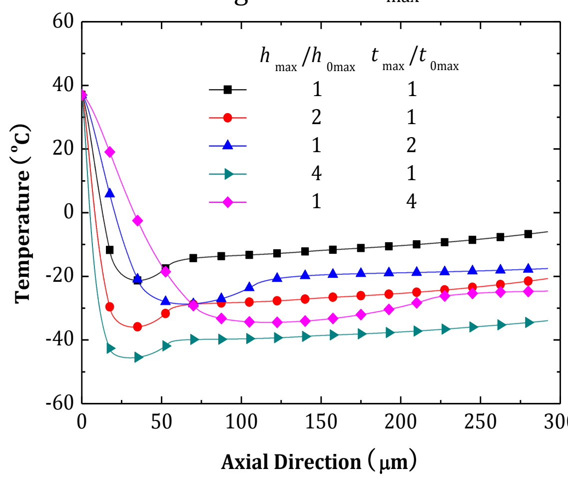
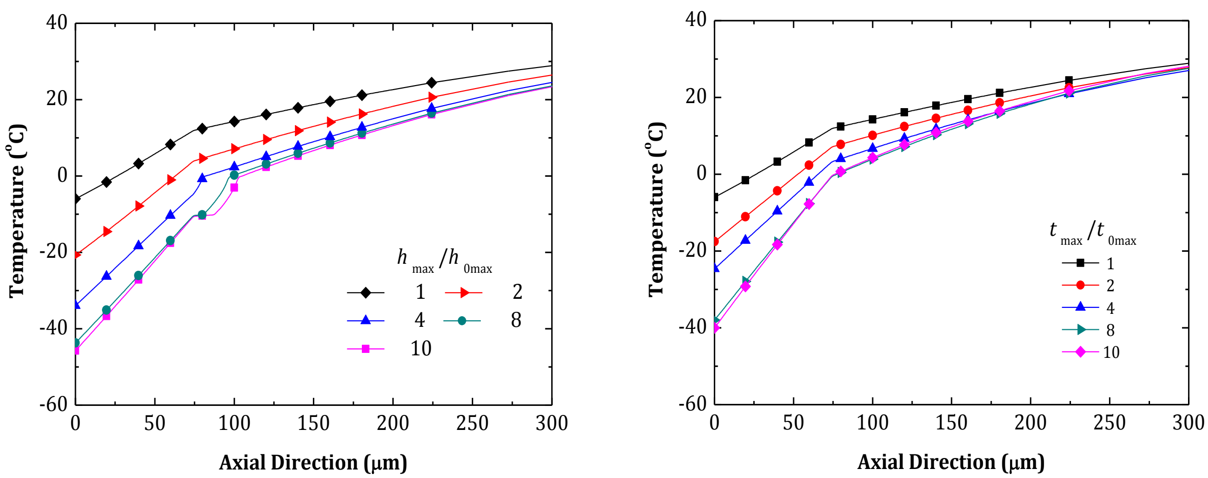


Fig 11. Effect of $h_{o,max}$ and t_{max} on surface temperature variation at the center of spray.

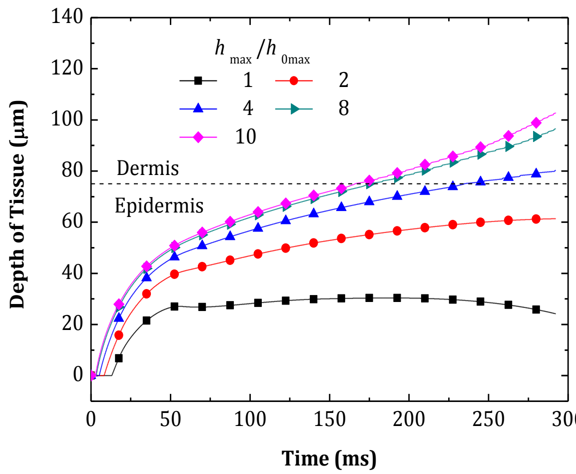
Figure 12 shows the effect of $h_{o,max}$ (a) and t_{max} (b) on the inner temperature distribution along the axial direction at the end of the spray. One finds from the figure 12a that a strong effect of $h_{o,max}$ on the inner temperature distribution. As $h_{o,max}$ increases, the surface temperature decreases, and the cold effect moves further inward. Such an effect will be vanished, however, as the $h_{o,max}$ reaches a certain value, due to limitation of the tissue heat conduction ability. One can also find a fairly strong effect of t_{max} on the inner temperature distribution in Figure 12b. As t_{max} increases, the surface temperature decreases, and the cold effect moves inward. Again, such an effect will be vanished eventually when t_{max} become too large, also due to the limitation of the tissue heat conduction ability.



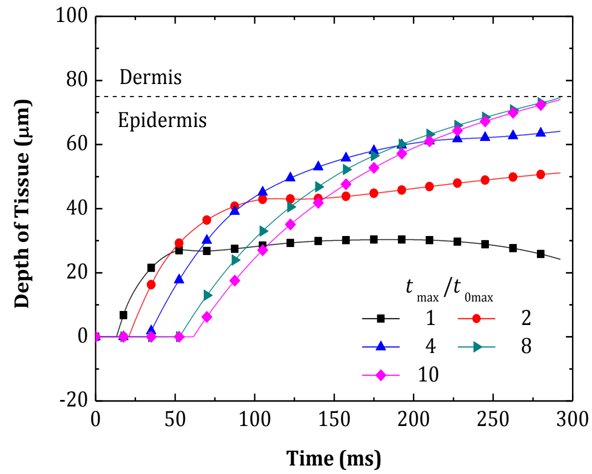
(a) (b)

Fig 12. Effect of $h_{o,max}$ (a) and t_{max} (b) on temperature distribution along tissue depth at end of spray

The effect of $h_{o,max}$ and t_{max} on the movement of the harmful isothermal of -0.5°C is given in Figure 13. As expected, the higher the $h_{o,max}$, the deeper the harmful isothermals penetrates inward. Such an effect eventually vanishes as the $h_{o,max}$ keeps increasing. For all cases including h_{max} = 10 $h_{o,max}$, however, the front of the mushy zone can't reach the dermal layer within 150 ms spray duration (which is sufficient in clinic use). The same is also true for an increased t_{max}.



(a)



(b)

Fig 13. Effect of $h_{o,max}$ (a) and t_{max} (b) the on the movement of the harmful isothermal of -0.5°C.

4. Conclusions

This study presents a theoretical model of cold injury of skin in cryogen spray cooling for dermatologic laser surgery. In order to examine the potential cold injury of skin cells, heat conduction equation was used to describe frozen and unfrozen zones, and heat capacity method was utilized for mushy zone to consider the phase change of tissue. A realistic boundary condition was implemented to simulate the cooling effect during cryogen spray cooling by a generalized correlation for the dynamic heat transfer coefficient. The model calculations indicate that the skin surface temperature exhibits a strong dynamic variation during CSC and there is a non-uniform cooling over the skin surface. The effects of the initial skin temperature (T_o), maximum value of heat transfer coefficient during spray ($h_{o,max}$) and time when $h_{o,max}$ occurs (t_{max}) were also investigated.

The hyperthermal injury may exist due to the low heat conduction ability of the skin. As a result, the insufficient protection in the axial direction should be taken into consideration in the clinic application. On the other hand, the inhomogeneity on the radial direction in cooling area has the risk to insufficient protection of skin at the margin of the spray. The insufficient protection on the radial direction on the skin surface should also be taken into consideration in the clinic application.

The spray cooling duration should be long enough to avoid uniform cooling along the radial direction and should be short enough not to induce cold injury. Based on our results, 100~150ms spray cooling duration is appropriate with the initial skin temperature higher than 20°C.

For a deep protection, a low room temperature (e.g. 20°C) is recommended. A large $h_{o,max}$ and t_{max} are preferable which may be carried out by substitution of new cryogen, adjust the position of the nozzle, and so on.

The cryogen spray cooling is a complicated process and needs to be controlled accurately. The cold effect should not be allowed to go too deep into the dermal layer to avoid cold injury, while should be deep enough to get a complete protection of the epidermis to avoid the hyperthermal injury after the laser irradiation.

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